FIBER-OPTIC ULTRASOUND SENSORS FOR SMART STRUCTURES APPLICATIONS

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EXECUTIVE SUMMARY

The goal of this project was to develop fiber-optic ultrasonic sensors to detect and characterize critical flaws in aircraft structures as part of a timely quantitative nondestructive evaluation (QNDE) program. Many critical areas of aircraft structures such as the interiors of fuel tanks and interfaces in multi-layered components are not readily accessible for inspection using conventional NDE techniques. Improved methods for the timely detection and characterization of flaws are therefore needed to assess the safety of aircraft structures. This project addressed the development of an important NDE tool utilizing fiber-optic ultrasonic sensors which can be permanently mounted in inaccessible regions of an airframe so as to facilitate flaw detection and characterization.

Over the course of this project, we have developed several types of intrinsic fiber-optic ultrasound sensors. These include the following fiber-optic ultrasound receivers:

- Fabry-Perot (FOFP) sensors,
- Sagnac Ultrasound Sensor (SUS), and
- Bragg-Grating Ultrasound (BGU) sensors.

We have also devised:

- fiber-optic laser ultrasound generator (FLUG) systems.

We have used the fiber-optic ultrasound systems developed here for flaw detection as well as process monitoring. Technology transfer of a system that was partially developed under this grant was accomplished through collaborative work with General Electric Corporate Research and Development (GECRD).

At the current state of art, we have determined that:

- Fiber-optic ultrasound receivers with excellent normal-incidence response can be configured as local (Fabry-Perot) or non-local (Sagnac) sensors. The Sagnac sensor is less complicated to fabricate, and maybe the sensor of choice for relatively narrowband ultrasound signals.
- The Bragg-grating sensor exhibits anomalous directionality behavior in that its sensitivity actually increases with angle of incidence of the ultrasound and is rather poor at normal incidence. From a practical standpoint, the Bragg-grating sensor can thus be used to complement the other sensors. A theoretical explanation for this behavior is still being developed. However, further work in this area is necessary to cast more light on the behavior of the Bragg-grating sensor.

- Fiber-optic laser ultrasound generators offer directional generation of ultrasound in a compact geometry. Further work in this area is necessary.

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John Dorighi, graduate student

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List of publications stemming from research effort:

1. Pavel Fomitchov, Alex Kromine, Sridhar Krishnaswamy, J.D. Achenbach, (1999), "Sagnac-Type Fiber-Optic Array Sensor for Detection of Bulk Ultrasonic Waves," to appear IEEE UFFC Transactions.

2. P. Fomitchov, Sridhar Krishnaswamy, J.D. Achenbach, (1999), "Intrinsic and Extrinsic Sagnac Ultrasound Sensor," to appear Optical Engineering.

3. Sridhar Krishnaswamy, (1998) "Fiber-Optic Sensors for Process Monitoring and Quality Control " in Sensing for Materials Characterization, Processing and Manufacturing, Vol. 1, ed G.A. Birnbaum and B. A. Auld, ASNT publications.

4. P. Fomitchov, Sridhar Krishnaswamy and J. D. Achenbach, (1997), "Compact phase-shifted Sagnac Interferometer for Ultrasound Detection," in Optics and Laser Technology, vol. 29, No. 6, pp.333-338, 1997.

5. J.F. Dorighi, Sridhar Krishnaswamy and J.D. Achenbach, (1997), "Response of an Embedded Fiber-Optic Ultrasound Sensor," Journal of the Acoustical Society of America, vol. 101, No. 1, pp. 257-263.

6. J.F. Dorighi, Sridhar Krishnasamy, and J.D. Achenbach, (1996), " A fiber optic ultrasonic system to monitor the cure of epoxy," in ASNT's Research in Nondestructive Evaluation, vol. 9, pp13-24.

7. P.A. Fomitchov, Sridhar Krishnaswamy, and J.D. Achenbach, (1999), "Intrinsic Fiber-Optic Sagnac Ultrasound Sensor for Process Monitoring in Composite Structures," SPIE vol. 3589, pp 156-159.

8. P. Fomitchov, Sridhar Krishnaswamy, and J.D. Achenbach, (1997), "Application of Sagnac Interferometer for Characterization of Scattered Ultrasonic Fields," Proceedings of the IEEE UFFC 1997 Symposium, Toronto, Oct. 5-8 1997.

9. J.F. Dorighi, Sridhar Krishnaswamy and J.D. Achenbach, (1996), "Sensitivity of an Embedded Fiber-Optic Ultrasonic Sensor," in Review of Progress in Quantitative Nondestructive Evaluation, ed. D.O. Thompson and D.E. Chimenti, vol. 16, Plenum Press, New York; {Seattle, Aug 1 -6, 1996}.

Fiber-Optic Ultrasound Sensors for Smart Structures Applications

I Introduction

1.1 Objectives: The goal of this project was to develop fiber-optic ultrasonic sensors to detect and characterize critical flaws in aircraft structures as part of a timely quantitative nondestructive evaluation (QNDE) program. QNDE is an interdisciplinary process encompassing quantitative measurement techniques to identify and characterize flaws, coupled with measurement models to interpret and relate the data to considerations of structural integrity and remaining life time of a component. The complete QNDE process therefore requires drawing on the resources of sensor technology, fracture mechanics and materials science to obtain reliable estimates of remaining safe life for a structure given the flaw characteristics as measured by a reliable NDE tool. In this project, the primary issues of sensor development, characterization and application were investigated.

1.2 Relevance to Air Force: The Air Force fleet must operate under diverse and often severe environmental conditions, and the methods of QNDE will play an increasing role in the in-service monitoring and maintenance of the currently aging fleet as well as of future structural systems incorporating advanced composite materials and metals. Flaw sites which are introduced into structural components during materials processing can be the source of fatigue cracking and corrosion damage which can severely compromise the structural integrity and effective performance of Air Force systems. Many critical areas of aircraft structures such as the interiors of fuel tanks and interfaces in multi-layered components are not readily accessible for inspection using conventional NDE techniques. Improved methods for the timely detection and characterization of flaws are therefore needed to assess the safety of aircraft structures. This project addressed the development of an important NDE tool utilizing fiber-optic ultrasonic sensors which can be permanently mounted in inaccessible regions of an airframe so as to facilitate flaw detection and characterization.

The ultimate goal of the project was to further the development of the concept of "active" structures. Active structures are structures that have an integrated array of sensors that can serve as a nervous system for structural health monitoring. These sensors are implanted in the material during composite materials processing (or retrofitted externally on metal structures) and can subsequently be used for continuous monitoring of the mechanical and material integrity of the structural components. This approach is expected to lead to better quality control of fabrication processes of composite materials, facilitate maintenance by providing continuous nondestructive evaluation of critical airframe structures, and can even be used in conjunction with embedded actuators to alter the geometric and vibrational characteristics of a structure. The active structures concept is finding increasingly wide application in areas ranging from advanced aerospace structures and adaptive optics (telescope mirrors etc), to more mundane structures such as bridges and high-rise buildings [Udd (1995)].

1.3 Fiber-Optic Ultrasound Sensors: Fiber-optic sensors, in particular, are beginning to play a significant role in QNDE of active or smart structures in view of their (i) relatively high sensitivity to temperature and strain variations; (ii) ease of multiplexing of several sensors thereby bringing unit cost down; (iii) potential for use near inflammable chemicals (e.g. fuel) where conventional electrical sensors might pose a fire hazard; and above all (iv) their ability to survive and perform in very adverse environments including high temperatures and high EMI [Udd (1995), Udd (1991), Grattan & Meggitt (1995)]. While most fiber-optic sensors for smart structures applications have targeted low-frequency strain and temperature measurement [Udd (1995)], or rely on fiber-breakage to indicate the presence of a flaw [Measures (1991)], our approach at Northwestern University has been to use *ultrasonic* probe signals for defect detection, and to use optical systems both for the generation and detection of the ultrasound probe signal. The main advantage of this approach is that it is a truly active integrated nondestructive system which makes use of the above-mentioned advantages of optical systems, but couples them with ultrasonic probe signals which have a higher sensitivity for detecting localized damaged regions than any of the currently used purely optical embedded NDE systems [Claus and Thompson (1991)]. Note also that this approach does not require that the flaw be in the immediate vicinity of the fiber sensor for it to be detected since the generated ultrasonic waves can be suitably directed to probe different regions of the structure. Another attractive feature of fiber-optic sensors is that they are very broadband detectors with frequency response well into the ultrasonic range, which makes them highly suitable for broadband acoustic and ultrasonic detection [Dorighi, Krishnaswamy & Achenbach (1995a)]. The detection can be passive to monitor acoustic emission signals and the vibrational modes of structures. Alternatively, in conjunction with pzt- or laser-generation of ultrasound these sensors can be used to actively probe the structure for incipient critical flaws.

2. Research Accomplishments

Over the course of this project, we have developed several types of intrinsic fiber-optic ultrasound sensors. These include the following fiber-optic ultrasound receivers:

- Fabry-Perot (FOFP) sensors,
- Sagnac Ultrasound Sensor (SUS), and

- Bragg-Grating Ultrasound (BGU) sensors.

We have also devised:

- fiber-optic laser ultrasound generator (FLUG) systems.

We have used the fiber-optic ultrasound systems developed here for process monitoring. We have also used the generation and detection systems for detection of simulated flaws. Technology transfer of a system that was partially developed under this grant was accomplished through collaborative work with General Electric Corporate Research and Development (GECRD).

We give below the details of each of these research accomplishments. Additional details are available in the cited references.

2.1 Fabry-Perot Ultrasound Sensors:

2.1.1 Sensor Fabrication: We have successfully completed the development of a frequency-stabilized intrinsic fiber-optic Fabry-Perot (FSI-FOFP) sensor for detection of ultrasound [Dorighi, Krishnaswamy, Achenbach (1995b)]. The fiber optic Fabry-Perot (see Fig. 1) consists of a partially mirrored fiber end face spliced to a small fiber length that has a mirror of approximately the same reflectivity at the other end. As with all interferometers, this sensor produces a change in output intensity which is related to the phase shift of light in the sensing region. Phase shifts are induced by changes in the length and refractive index of the sensing fiber. In order to maintain quadrature we have implemented an active homodyne stabilization technique which controls the laser frequency to compensate for sensor drift.

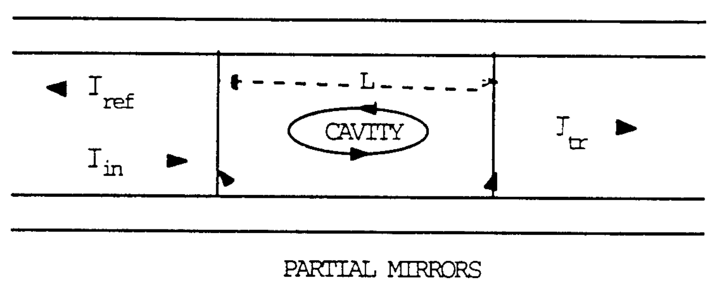

Figure 1: Schematic of intrinsic fiber optic Fabry-Perot.

2.1.2 Sensor Characterization: We have also evaluated the frequency response of the ultrasonic FOFP sensor [Dorighi, Krishnaswamy, Achenbach (1997)]. This is essential for correct quantitative interpretation of the acquired data. We have developed analytical FOFP frequency response models by considering the elastodynamic problem of harmonic plane waves impinging at an angle to the axis of a cylinder (the fiber) embedded in an infinite elastic medium (the bulk structure) as shown in Fig. 2.

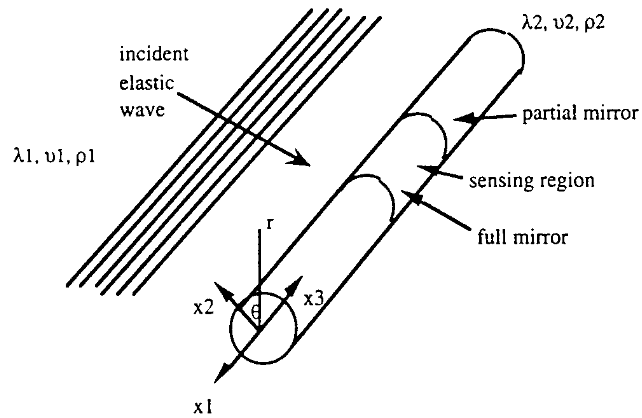

Figure 2: Geometry for analysis

Once the strain induced in the fiber is calculated from the above elastodynamic analysis, a phase-strain model is used to calculate the expected response of the FOFP for various frequencies of the impinging ultrasound and at various angles. We have also done experiments to simulate the theory and to verify the theoretical predictions. The comparison between the results and the experiments are encouraging (Figs.3).

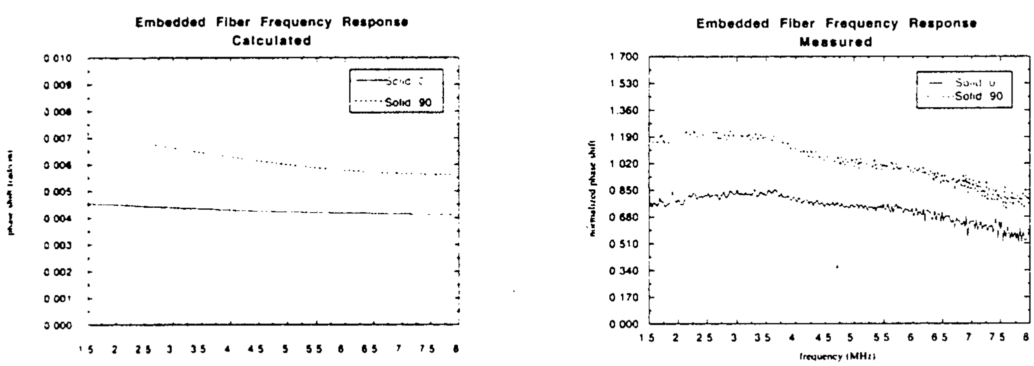

Fig. 3: Theoretical and measured frequency response for fiber sensor in epoxy.

2.1.3 Sensor Applications: We also have preliminary results on intrinsic and extrinsic laser generation of ultrasound, and we have shown that the signal-to-noise performance of the FSI-FOFP is sufficient to enable the detection of the rather small amplitude ultrasound that is typically generated by laser thermoelastic generation (see Figs.4-5).

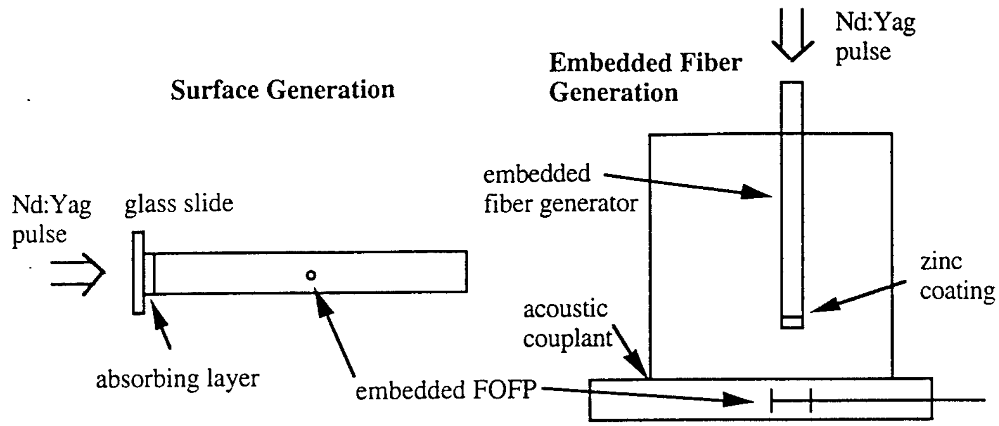

Figure 4: Configurations for (a) surface and (b) interior laser generation of ultrasound.

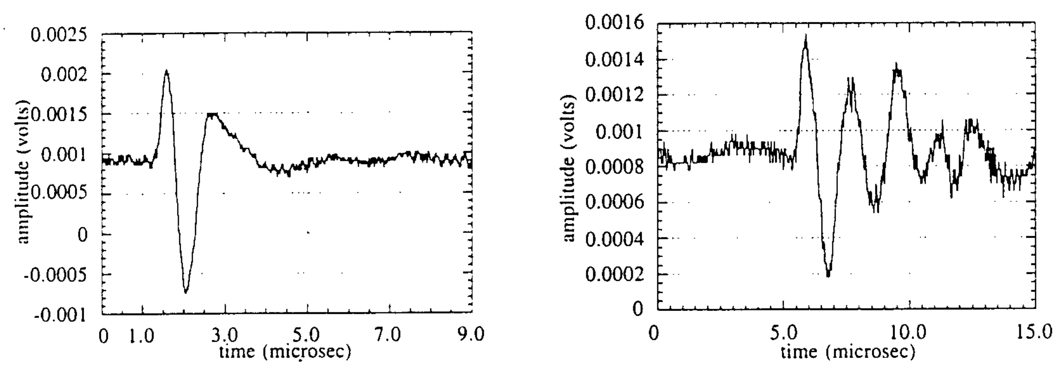

Figure 5: (a) Surface and (b) interior laser-generated ultrasound as detected by FSI-FOFP.

The FSI-FOFP sensor was also used to detect the presence of a small hole in an epoxy plate [Dorighi, 1996]. The schematic of the setup is shown in Fig. 6a. A pzt-transducer used to generate the ultrasound. The first pass and reflected signals (if any) from the hole were monitored for various transducer positions. The ratio of the reflected to the incident signal is plotted in Fig. 6b for different positions of the transducer. The presence of the strong reflected signal for certain transducer positions indicates reflection from the hole.

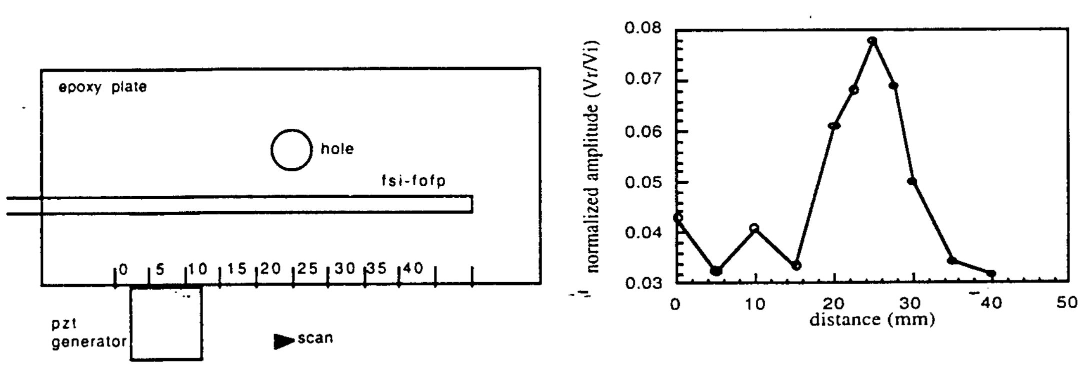

Figure 6: (a) Geometry and (b) defect reflectivity as sensed by the FSI-FOFP sensor.

2.2 Sagnac Ultrasound Sensors:

2.2.1 Sensor Development: Fabrication of the above Fabry-Perot sensor requires optically polishing the ends of the fiber, partially mirrorizing them, and then fusion splicing them. The fusion splicing process is rather cumbersome resulting in a sensor yield that is only about 30% (that is only one in three sensors works). In view of this, we have developed a non-local Sagnac Ultrasound Sensor that does not require fusion splicing [Fomitchov, Krishnaswamy, and Achenbach (1997, 1999a)].

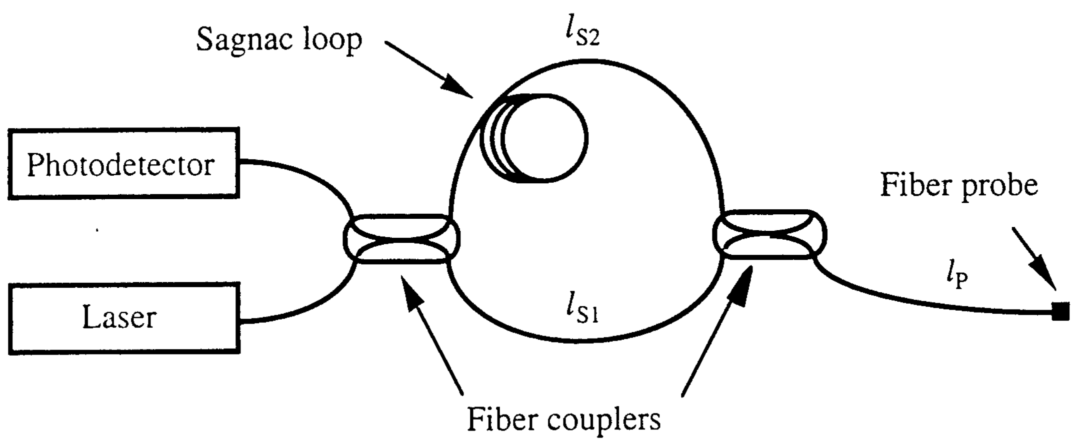

Fig. 7: Schematic of the intrinsic Sagnac Ultrasound Sensor

The sensor is shown schematically in Fig.7. The sensing segments of the optical fiber are mirrorized at the ends (with no fusion splicing required). Light gets totally reflected from the probe end and is processed by the Sagnac interferometer. The Sagnac interferometer has many advantages over other interferometric systems, which make it attractive for many industrial applications:

(i) It is truly path-matched and does not require active stabilization and it can thus be used in a noisy environment.

(ii) Quadrature biasing is done using a frequency-shifting technique which is much less noisy than the serrodyne phase-modulation scheme used in Fomitchov, Krishnaswamy, and Achenbach (1997).

(iii) The frequency-shifting technique enables frequency separation of useful interferences from parasitic interferences.

(iv) The system can be completely fiberized for remote operation in hard-to-access regions of a structure, and it can be designed as a small portable device suitable for field applications.

2.2.2 Sensor Characterization: The SUS was characterized in a series of experiments to reveal its sensitivity, directionality and frequency response in a manner similar to that used for the Fabry-Perot [Fomitchov, Krishnaswamy, and Achenbach (1999a)]. The smallest optical phase shift that can be detected using the current system was determined to be 3.6 mrad over a 6 MHz detection bandwidth. The SUS was also found to be a highly directional receiver with sensitivity rolling off to essentially zero at ultrasound incidence angles greater than a few degrees.

2.2.3: Sensor Applications: An example application of the Sagnac Ultrasound Sensor is shown schematically in Fig.8a. A U-shaped Sagnac fiber probe is embedded in an epoxy block. The ultrasonic wave generated by the pzt impinges on the sensor twice, affecting the phase of the light propagating inside the fiber. The resulting Sagnac-demodulated signal is shown in Fig.8b showing both the first pass and the second pass signals. Measurement of wavespeeds and attenuation can be made from such experiments [Fomitchov, Krishnaswamy, and Achenbach (1999a)].

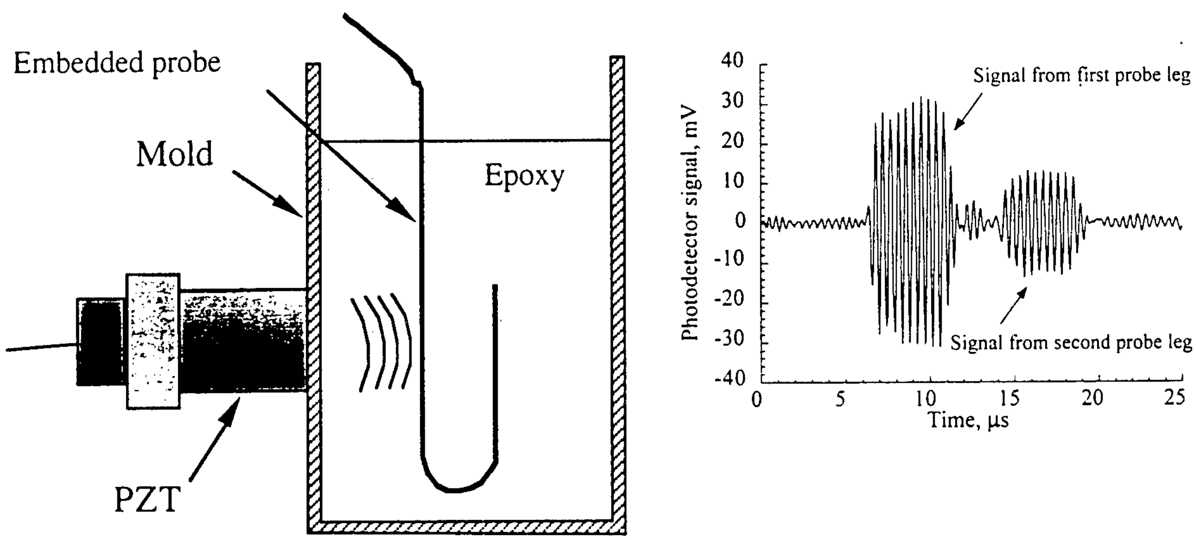

Fig. 8 (a) Sagnac sensor embedded in epoxy; (b) signal detected.

2 2.4 Sagnac Ultrasound Sensor Coils Sagnac Ultrasound Sensors can be configured into *array* sensors by making the fiber probe in the form of a coil. By multiply folding the probe fiber to obtain a sensor coil (Fig. 9a), the sensitivity of the sensor can be increased significantly, as can be seen from the results in Fig. 9b. This is because the interaction length between the acoustic beam and the sensor is increased in a Sagnac coil [Fomitchov, Krishnaswamy, and Achenbach (1999b).].

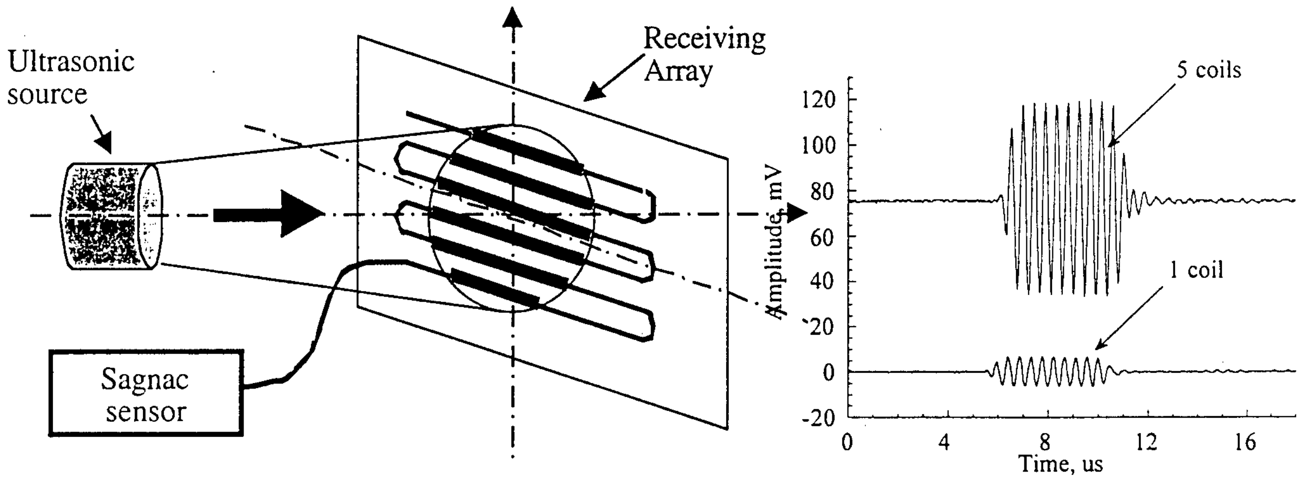

Figure 9. (a) Sagnac Ultrasound Sensor Coil, and (b) sensitivity for various coil loops.

2.3 Bragg-grating Ultrasound Sensor: Recently, fiber Bragg-grating sensors have been gaining attention primarily due to their ease of fabrication and their ability to be multiplexed with minimal difficulty. These sensors, as currently used, consist of Bragg-gratings -- refractive index modulations in the fiber core along the waveguide axis -- written into the fiber as shown in fig. 1a. These gratings act as reflection filters which strongly reflect certain wavelengths which depend on the pitch of the gratings. The reflectivity depends on the depth of the refractive index modulation. If strain and/or temperature cause a change in the pitch, the reflected wavelength spectrum will shift accordingly and this can be monitored interferometrically or with a spectrum analyzer. Sensors to measure static strain and temperature have been devised based on this principle.

We have used the Bragg-grating sensor as an ultrasound sensor as follows (Fig. 10a). A single Bragg-grating of nominal pitch Λ is written over a length L of a single-mode fiber. The pitch is chosen so as to have a relatively broad reflectance spectrum peak within the tuning range of an external cavity tunable laser diode that we have in our lab. This laser, which has a sufficiently narrow line width, is tuned to the "lock-point" shown in fig 10b. Ultrasonic plane waves of extent much larger than length L are directed normal to the fiber sensor axis. As the ultrasound impinges on the sensor, its reflectance spectrum changes, and this manifests itself as a high-frequency fluctuation of the reflected intensity.

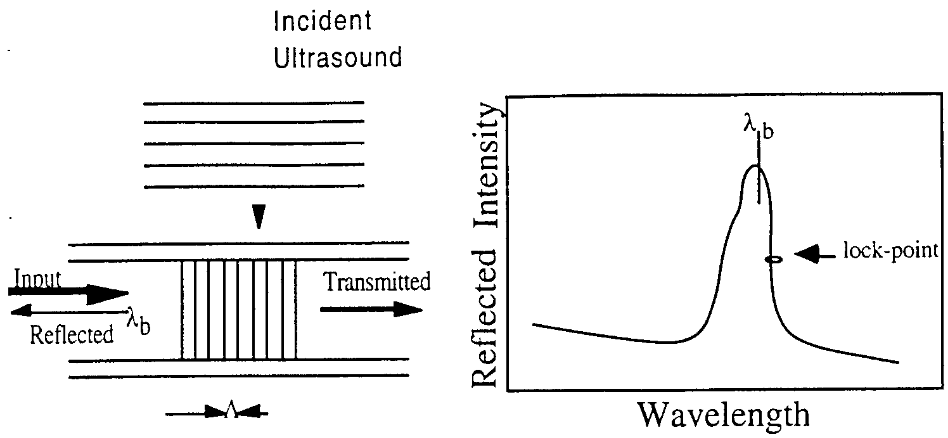

Fig.10: (a) Bragg-grating ultrasound sensor and (b) its spectrum

Results from using such a sensor are shown in Fig. 11. In this case, the impinging ultrasound was toneburst propagating normal to the axis of the fiber. The response of the Bragg-grating sensor to ultrasound impinging at an angle is currently being studied. One unusual feature that has emerged is that the sensitivity of the Bragg-grating ultrasound sensor is higher at an angle than at normal incidence! This isssue is still under investigation.

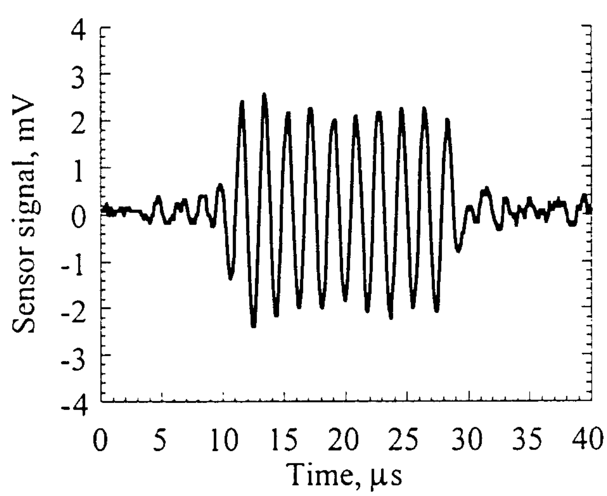

Figure 11: Ultrasonic toneburst detected by the Bragg-grating sensor.

2.4 Fiber Generation of Ultrasound:

The effort in this area has just begun. We have developed fiber-optic laser ultrasonic generator (FLUG) sources that can be embedded in a structure to generate ultrasound from within it. The light from a high-power Nd:YAG laser is coupled into a 200μm multimode optical fiber

(Fig. 12). The other tip of the fiber is suitably coated with an absorbing layer. The laser energy is absorbed at the tip, leading to rapid thermal expansion and the consequent generation of ultrasound.

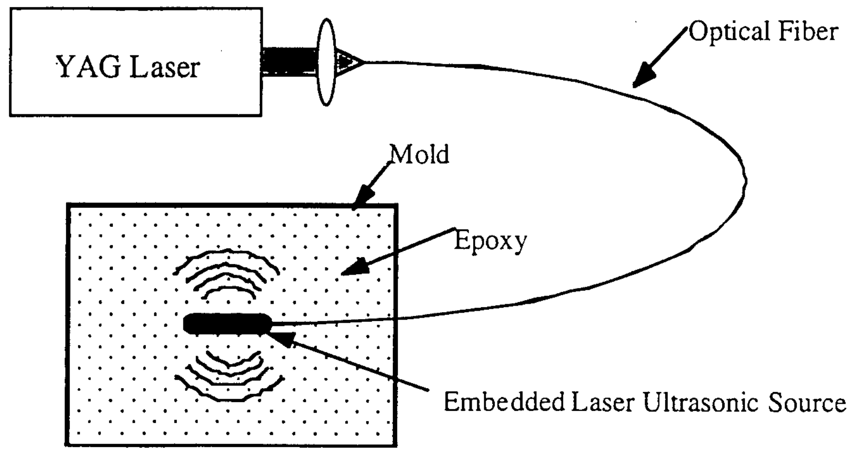

Fig.12: Embeddable Fiber-Optic Laser Ultrasonic Source

We have devised FLUGs that can generate ultrasound (a) parallel to, (b) normal to and (c) at arbitrary angles to the fiber axis. The directivity pattern for an angled FLUG shown in Fig.13a is shown in Fig. 13b. It can be seen that it is possible to devise FLUGs with the desired directionality.

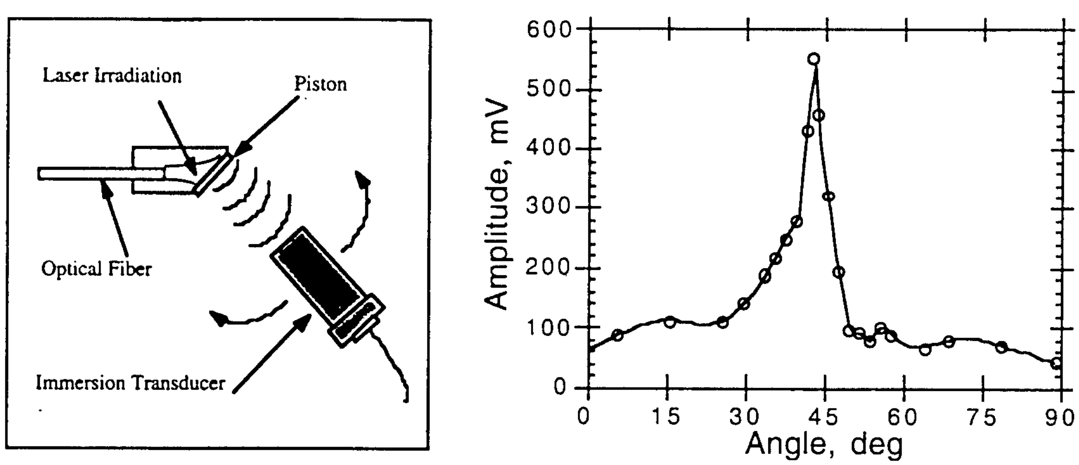

Fig. 13: (a) Angled FLUG, and (b) directivity of generation

Efforts are underway to implement a complete laser-based embedded fiber-optic ultrasound generation and receiver system for NDE applications.

3. Transitions:

The Sagnac Ultrasound Sensor (SUS) is being adapted for a specific General Electric aerospace application. Northwestern University has a contract from GE CRD to effect this technology transfer process. Significant progress has been made, and the first phase of the tech transfer process is expected to be complete by Dec. 1999. Other interactions include discussions with and demonstrations to various visitors to our labs.

4. Conclusions:

At the current state of art, we have determined that:

- Fiber-optic ultrasound receivers with excellent normal-incidence response can be configured as local (Fabry-Perot) or non-local (Sagnac) sensors. The Sagnac sensor is less complicated to fabricate, and maybe the sensor of choice for relatively narrowband ultrasound signals.
- The Bragg-grating sensor exhibits anomalous directionality behavior in that its sensitivity actually increases with angle of incidence of the ultrasound and is rather poor at normal incidence. From a practical standpoint, the Bragg-grating sensor can thus be used to complement the other sensors. A theoretical explanation for this behavior is still being developed. However, further work in this area is necessary to cast more light on the behavior of the Bragg-grating sensor.
- Fiber-optic laser ultrasound generators offer directional generation of ultrasound in a compact geometry. Further work in this area is necessary.

5. References:

Claus R.O. and C.D. Thompson, (1991), *Optical Fiber-Based Ultrasonic Wave Generation and Detection in Materials,* Review of Progress in Quantitative Nondestructive Evaluation, vol. 10B, Plenum press, New York.

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Dorighi, J.F., Sridhar Krishnaswamy and Jan D. Achenbach, (1995b), "A Stabilization Scheme for Embedded Fiber-Optic Fabry-Perot Sensors for Ultrasound Detection," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, vol .42, No. 5.

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14. ABSTRACT The project addressed the development of an important nondestructive evaluation tool utilizing fiber-optic ultrasonic sensors which can be permanently mounted in inaccessible regions of an airframe so as to facilitate flaw detection and characterization. Over the course of this project, several types of intrinsic fiber-optic ultrasound sensors were developed. These include the following fiber-optic ultrasound receivers: Fabry-Perot (FOFP) sensors, Sagnac Ultrasound Sensor (SUS), and Bragg-Grating Ultrasound (BGU) sensors. Fiber-optic laser ultrasound generator (FLUG) systems were also developed. Applications of these fiber-optic ultrasound systems in process monitoring as well as flaw detection have been demonstrated.

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